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Effects of extreme natural events on the provision of ecosystem services in a mountain environment: the importance of trail design in delivering system resilience and ecosystem service co-benefits

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Abstract

A continued supply of ecosystem services (ES) from a system depends on the resilience of that system to withstand shocks and perturbations. In many parts of the world, climate change is leading to an increased frequency of extreme weather events, potentially influencing ES provision. Our study of the effects of an intense rainfall event in Gorce National Park, Poland, shows: (1) the intense rainfall event impacted heavily on the supply of ES by limiting potential recreation opportunities and reducing erosion prevention; (2) these negative impacts were not only restricted to the period of the extreme event but persisted for up to several years, depending on the pre-event trail conditions and post-event management activities; (3) to restore the pre-event supply of ES, economic investments were required in the form of active repairs to trails, which, in Gorce National Park, were an order of magnitude higher than the costs of normal trail maintenance; and (4) when recreational trails were left to natural restoration, loss of biodiversity was observed, and recovery rates of ES (recreation opportunities and soil erosion prevention) were reduced in comparison to their pre-event state. We conclude that proper trail design and construction provides a good solution to avoid some of the negative impacts of extreme events on recreation, as well as offering co-benefits in terms of protecting biodiversity and enhancing the supply of regulating services such as erosion prevention.

Highlights

- Supply of ecosystem services (ES) declined as a result of an intense rainfall event
- Negative impacts of this extreme event persisted for up to several years
- Restoration of the pre-event supply of ES required economic investments
- Proper trail construction avoids some of the negative impacts of extreme weather

Keywords: erosion, recreation, trail impact, intense rainfall, trail restoration, Gorce National Park

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1. Introduction

The concept of ecosystem services (ES) has recently become a very popular framework in environmental management (e.g. Burkhard et al., 2012; Jacobs et al., 2014; Kareiva, 2011), despite the controversy over how, and if at all, we should quantify the value of nature in monetary units (Bockstael et al., 2000; Daily et al., 2000; McCauley, 2006). ES are identified as the benefits which society obtains (directly or indirectly) from ecosystems. The three main groups of ecosystem services are: provisioning (e.g. freshwater, crops, timber), regulating (e.g. water purification, erosion prevention) and cultural (e.g. recreation, aesthetics). The general concept of ES is well known and widely described (Bolund and Hunhammar, 1999; Carpenter et al., 2009; De Groot et al., 2002; Millennium Ecosystem Assessment, 2005a, 2005b). However, the transition from the general concept to more detailed theoretical and/or practical approaches related to specific aspects of ES and landscape characteristics remains challenging.

Cultural ecosystem services (CES), which are defined as "non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experience" (Millennium Ecosystem Assessment, 2005a), are among the least frequently-studied ES. This is because they are complex and multi-faceted, and it can be difficult to develop appropriate spatial indicators to represent them (Daniel et al., 2012; Hernández-Morcillo et al., 2013; Martínez-Harms and Balvanera, 2012). Therefore, there is a need for further research concerning the quantification and spatial distribution of the provision and supply of CES, to provide data to support more integrated land use planning (e.g. Goldman and Tallis, 2009; Goldstein et al., 2012).

A continued supply of CES from a system is reliant on the resilience of that system to withstand shocks and perturbations. In many parts of the world, climate change is leading to an increased frequency of extreme weather events (Beniston and Stephenson, 2004; Coumou and Rahmstorf, 2012; IPCC, 2012; Jentsch and Beierkuhnlein, 2008; Mirza, 2003; Planton et al., 2008; Van Aalst, 2006). These extreme events can threaten the provision of ES (e.g. Bangash et al., 2013; Terrado et al., 2014), including CES. However, the impact of extreme events on CES has received very little attention.

Here, we describe the impact of extreme weather, in the form of an intense rainfall event, on the provision of CES within a protected mountain environment. Protected natural areas (PNAs), such as National Parks, are managed mainly for two purposes: nature or landscape conservation and recreation (Dudley, 2008). PNAs are usually located in regions of scenic beauty (e.g. coasts, mountains) and/or areas rich in biodiversity (Adamowicz et al., 2011). Hence, they have substantial potential to be a source of CES (Leung and Marion, 2000; Siikamäki, 2011). Biodiversity is also important in its own right as a supporting ES (Millennium Ecosystem Assessment, 2005a), and there is growing evidence that it can contribute significantly to enhanced health and wellbeing (Clark et al., 2014; Keesing et al., 2010; Sandifer et al., 2015; Taylor and Hochuli, 2014).

To maximize delivery of CES, PNAs must be managed so that appropriate infrastructure for visitors is provided. Recreational trails are particularly important in providing visitor access to remote destinations (Cole, 1993; Olive and Marion, 2009), and support activities such as walking, rock climbing, bicycling and horseback riding. Of these, walking is considered to be the most popular (Simmons, 2013). As an example, according to the Central Statistics Office in Poland, the number of beneficiaries of recreational ecosystem services (measured as a number of visitors in 23 National Parks, which cover 1% of the country) was approximately 12 million per year. For these visitors, nearly 3,600 km of recreational trails (mainly walking and bicycling) were prepared (CSO, 2013).

Recreational use of trails, if not handled properly, can cause severe impacts through trampling damage, including soil erosion, muddiness, trail widening and, in the long term, changes in plant composition. These problems have been described from all around the world (e.g. Arrowsmith and Inbakaran, 2002;

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Ballantyne and Pickering, 2015; Belnap, 1998; Cole, 1993; Dixon et al., 2004; Hill and Pickering, 2006; Leung and Marion, 1996, 2000; Marion et al., 1993; Monz et al., 2010; Ólafsdóttir and Runnström, 2013; Özcan et al., 2013; Pickering et al., 2010; Tomczyk, 2011; Tomczyk and Ewertowski, 2013b). Extreme weather events, particularly intense rainfall, have similar adverse effects on trails. Erosion regulation capacity can be quickly exceeded, resulting in the loss of vegetation, which further exacerbates erosion, since bare soil is more prone to soil erosion than vegetated soil (Olive and Marion, 2009; Tomczyk and Ewertowski, 2013b). This will have knock-on consequences for CES, specifically recreation, since degraded trails have a negative impact on visitor numbers, experience and safety (Hammitt et al., 2015; Kim et al., 2003; Kim and Shelby, 2006; Moore et al., 2012; Roggenbuck et al., 1993; Verlič et al., 2015). Adverse impacts on trails may be limited to some extent by appropriate management activities such as planning, robust construction and regular maintenance (Cole, 1993; Leung and Marion, 1996; Olive and Marion, 2009; Wimpey and Marion, 2010). However, evaluations of management practices related to trail rehabilitation remain limited and have not previously been conducted within an ES framework.

In this paper, we build on a long-term study of recreation in Gorce National Park (GNP) in Poland to model the impact of an intense rainfall event on three types of ecosystem services in the Park: a supporting service (biodiversity); a regulating service (erosion prevention); and a cultural service (recreation). We also evaluate the cost and effectiveness of alternative management strategies in effecting the recovery of these different services following the rainfall event.

2. Study Settings

2.1. Gorce National Park

Gorce National Park (GNP), comprising the Gorce Mountains (1311 m a.s.l.), is situated in the outer Carpathians mountain system (the Beskidy Mountains) in southern Poland (Fig. 1). The study area covers an area of 70.3 km^2. Most of GNP belongs to the state (94%), with the remainder (6%) being in private ownership. Forests are the main type of land cover (94%) (Ruciński and Tomasiewicz, 2006). Apart from the forests, GNP also includes an abundance of areas of high biodiversity value, especially its glades and pastures. Because of the natural character of its landscapes, which offer scenic views of the surrounding mountains, the Park is popular with visitors from the whole country (Semczuk, 2012).

Recreational trails in Gorce National Park are single or multi-use and hiking is the most popular activity – walkers constitute 96-98% of the Park visitors (Popko-Tomasiewicz, 2006; Semczuk, 2012). According to the estimation by CSO (2011, 2012, 2013), visitors in GNP increased in numbers from 60,000 in 2010, to 65,000 in 2011 and 70,000 in 2012.

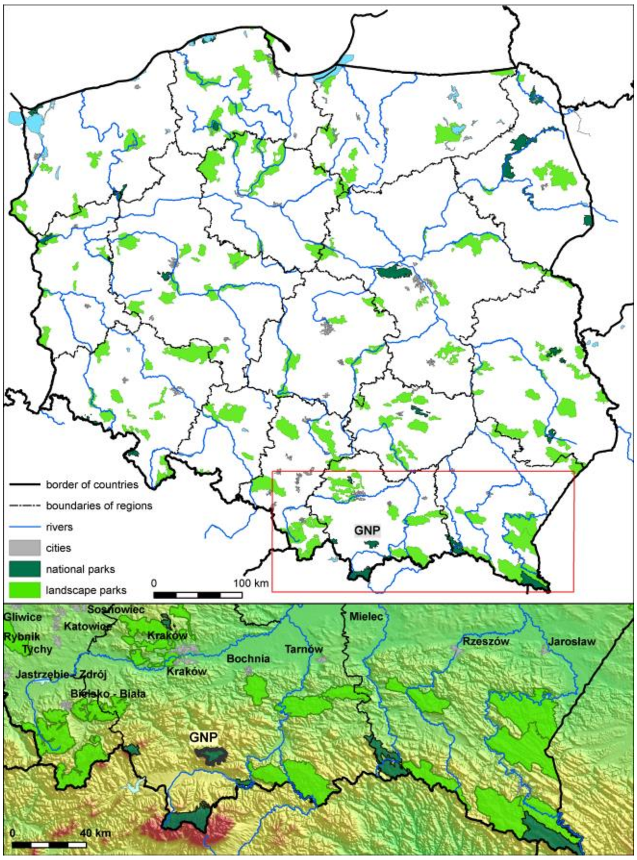

Figure 1. Location of the study area within Poland. (Reprinted from Applied Geography, 31, A.M. Tomczyk, Copyright (2011), with permission from Elsevier).

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2.2. Extreme weather event: intense rainfall in May 2010

In May 2010, a large part of Europe (including the southern part of Poland) was affected by extreme rainfall events during a short period lasting a few days. More than 2,000 mm of rain fell during a 24-hours period on 16th-17th May, and in many places in the Beskidy Mountains, the amount of precipitation between 16 and 19 May was 1.5-3 times more than monthly long-term mean for 1951–2000 (Bissolli et al., 2011; Woźniak, 2013). The situation was similar for GNP, where typically, a mean annual precipitation varies from 700 mm in the foothills to 1200 mm at the highest altitudes (Miczyński, 2006). As precipitation was also recorded at the beginning of May 2010, the water retention capacity of the soil was already very limited. Hence, these heavy rainfall events caused serious problems in many lowland areas due to flooding and increased sedimentation rates (Bissolli et al., 2011; Skolasińska et al., 2014; Wierzbicki et al., 2013). In upland and mountain areas, the rainfall intensified soil erosion and initiated mass movements of soil, with consequent delivery of debris to streams and rivers and damage to infrastructure such as houses, roads and bridges.

3. Methods

3.1. Scenario development

We estimated the provision of supporting (biodiversity), regulating (erosion prevention) and cultural (recreation) ecosystem services for four different scenarios and five time periods. The four scenarios were:

- Scenario 0 – background scenario, i.e. an area is unavailable to visitors for conservation reasons and no recreational trails have been constructed.
- Scenario 1 – well designed, constructed and maintained trails which were not destroyed during the extreme rainfall event.
- Scenario 2 – trails damaged by surface water runoff from the heavy rainfall, but which were subsequently repaired.
- Scenario 3 – trails damaged by surface water runoff from the heavy rainfall, but which were not then repaired, but left for recovery through natural processes (i.e. no active management activities).

The five time periods considered were:

- Period 1 (pre-event normal functioning) – normal functioning, with trails in a satisfactory condition; the period before the extreme event (summer 2007 [the beginning of our field surveys in GNP] - spring 2010).
- Period 2 (extreme event, intense rainfall) – the period during and immediately following the heavy rainfall, which is characterised by an increase in surface water runoff (May 2010).
- Period 3 (repair) – the period when repairs to trails occurred; valid only for scenario 2 (summer 2010 – autumn 2014).
- Period 4 (natural restoration) – the time when trails recovered through natural processes; valid for scenario 3 (from May 2010 onwards, natural restoration could be still incomplete) and for scenario 2 (recovery from disturbances related to trail repair).
- Period 5 (post-event normal functioning) – normal functioning of trails; the period when trails and their surroundings are functioning normally once more, and in a satisfactory condition (after May 2010 for scenarios 0 and 1, after finishing the repairs for scenario 2, not applicable to scenario 3).

We studied scenarios 1-3 using five case studies, located in various part of GNP (Fig. A1). They were selected to ensure representation of different elements: environmental conditions (land cover, slope, aspect, trail alignment, soil type); presence of management activities (repaired trails versus unrepaired ones); and appearance of degradation (normal functioning of trails versus degraded trails).

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3.2. Quantification of ecosystem services

Erosion prevention and biodiversity

Indicators of erosion prevention and biodiversity maintenance were calculated based mainly on field data. The first period of field work covered normal functioning of recreational trails (summer 2007 – spring 2010) to provide an overview of the baseline condition. The effects of the extreme rainfall event were mapped in May 2010, immediately after it occurred. In subsequent seasons (i.e. autumn 2010 – autumn 2014), field mapping and surveying were focused on recording trail recovery and the effectiveness of repair actions.

The ecosystem service of erosion prevention was quantified using soil loss as an inverse indicator. Soil loss was measured applying a variable interval Cross-Sectional Area (CSA) method proposed by Marion and Olive (2006). For each case study, soil loss was measured in several profiles (5-11) and the value of soil loss was taken as the mean soil loss across these profiles. The first measurement session recorded soil loss in relation to the ground level during the time of trail construction. Subsequent measurement sessions demonstrated soil loss or deposition through time, allowing us to assess the direction and extent of changes since the previous session. In addition to the field measurements, the level of soil loss in an area not affected by direct recreational impacts was modelled using the Universal Soil Loss Equation (USLE), following the method of Tomczyk (2011).

Maintenance of biodiversity was assessed using trail width as an inverse proxy. We measured the width of trampling disturbance of ground vegetation and organic litter across the trail, as evident from completely destroyed vegetation cover and trampled, broken plants (cf. Tomczyk and Ewertowski, 2011).

Recreation

The number of visitors mentioned in section 2.1 represents beneficiaries of recreation services. This number might be lower or higher than the capacity of a specific area to receive visitor traffic without causing unacceptable changes to the environment and without spoiling the visitors' perception of wilderness. We made an attempt to estimate number of visitors, which would be acceptable from both environmental and sociological perspectives. We proposed a simple model based on various concepts available in literature (Arnberger et al., 2010; Manning, 2001, 2005; Manning and Freimund, 2004; Newman et al., 2005), whereby the number of groups (as a proxy for number of visitors) which can be accommodated by a trail section during one day (*N*) was calculated as follows:

$$N = \frac{V}{d} h \cdot k \cdot w,$$

where V is average walking pace in m/s, d is a distance between groups of visitors in m, h is a number of hours per day during which most of recreation traffic is recorded, k is trail condition factor (ordinal variable), and w is trail width factor (ordinal variable). Values of the coefficients should be adjusted according to the specific characteristics of the protected area studied. For GNP, the relevant contextual information is as follows:

1) Trail crowding is a situation in which interaction with other visitors is greater than a desirable level (Graefe et al., 1984; Gramann and Burdge, 1984). Most visitors to GNP wish to experience it for its wild nature and natural areas (Semczuk et al., 2014). We assumed that 300 m (value d) would be an appropriate distance between hiking groups (including single hikers) that allows them to have this experience without disturbing or being disturbed by too many following or preceding people. At the same time, encounters with hiking groups from the opposite direction will avoid the feeling of complete loneliness or isolation.
2) Walking pace (V) is related to environmental condition, including especially the slope of trail. The influence of trail slope on walking speed was calculated using method described by Rees (2004): $\frac{1}{v} = a + bm + cm^2$, where v is the speed of the trail user in m/s, m is trail slope in

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degree and *a, b, c* are coefficients. Values for the coefficients, used in this study, were adopted from Rees (2004), i.e. a = 0.75, b = 0.09 and c=14.6.

3) The majority of recreation visits during the summer season are between 8 am and 8 pm, so h = 12.
4) We applied simplified values to describe trail condition: k = 1 represented non-degraded, well-prepared trails, and k = 0.5 was used for trails severely impacted by soil erosion. We assumed that walking speed on uneven and rough surfaces was halved.
5) The potential amount of visitors on a trail is also related to designated trail width. Wider trails can accommodate more visitors than narrower ones, at the same time avoiding or minimising trail impacts. Based on results of our observations, we proposed the following values for the w coefficient:
   - w = 1 for trails narrower than 0.5 m, which can accommodate a single line of visitors (one by one);
   - w = 2 for trails from 0.5 to 1.2 m wide, which can accommodate visitors walking side by side;
   - w = 3 for forest roads wider than 1.2 m, which can accommodate a larger group of people (up to 5 people at one time).

We assumed that trail capacity during an extreme rainfall event is 0. This is a consequence of the threats to health and safety posed by heavy rain and strong wind, i.e. there is a high risk of slipping and falling down, and falling trees and branches could injure or even kill trail users. Thus, during severe weather conditions in GNP, it is recommended not to use trails (GNP, 2012), and visitors themselves are also less likely to travel (George, 1993; Li and Lin, 2012). We acknowledge that there are limitations of using the carrying capacity approach (c.f. Lindberg et al., 1997), and the above numbers should therefore be used as indicative values only. The primary goal of the estimations is to demonstrate the impact of rainstorm event on ES provision and to compare relative impacts on different sites under different scenarios.

4. Results

4.1. Baseline – the condition of recreational trails before 2010

The trail condition before the extreme rainfall in 2010 represents the baseline of our study. Although GNP experiences relatively low visitor numbers in relation to other national parks in Poland, trail impacts were substantial (Tomczyk and Ewertowski, 2011). The trail width ranged from 0.3 m to 24.5 m, with a mean of 2.4 m (Fig. A2). In total, the 55.1 km of analysed trails covered an area of 139,000 m^2, of which 130,000 m^2 was exposed soil. The trail incision ranged from 0 to 3.4 m in depth (Fig. A2).

4.2. Environmental effects of intense rainfall

The intense rainfall in May 2010 caused a variety of damage within the Park area. The most important effects were the following (Fig. 2): (1) development of erosional rills on trail treads; (2) damage or destruction of bridges, culverts and water bars; (3) creation of extensive muddy sections; and (4) overall increase in soil erosion. These degradation problems created difficult and unsafe travel conditions. Visitors, trying to avoid these difficulties, started to trample trailside vegetation, leading to the additional widening of the trail tread. Moreover, in several places, alternative (informal) sections of trails were developed by users. Among other consequences of the intense rainfall were a rise in delivery of sediments into streams and retention ponds following soil erosion, and an increase in flood risk, which affected not only the Park area, but also areas downstream.

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Figure 2. Examples of impacts in Gorce National Park related to the extreme rainfall event in May 2010: (a) damage to trail tread due to small landslide; (b) creation of muddy sections; (c), (d), (e) development of erosional rills destroying trail tread;(f) undercutting of trail treads by a stream; (g) increase in delivery of sediments due to soil erosion.

4.3. Impacts of the intense rainfall event on ES provision

4.3.1. Scenario 0 – area not designated for visitors

Recreational use in GNP is permitted only through recreational trails. These trails provide access to spatially distributed tourist attractions and simultaneously limit recreation to specific places. Therefore, most of the Park's area is unavailable for visitors and constitutes background conditions; on one hand, it therefore represents a maximum amount of erosion prevention service available from each specific landscape, but on the other hand, it provides no recreational opportunities (Table 1, Fig. 3). The given values of soil loss represent an averaged value which was modelled for soil erosion within the Park area. As no recreation opportunities are provided under this scenario, no biodiversity degradation occurs due to the impact of recreation (Table 1, Fig. 3).

4.3.2. Scenario 1 – well-designed trail

Scenario 1 represented the situation in which trails were properly constructed and maintained, and therefore, no significant damages occurred after the heavy rainfall in May 2010 (Fig. 4a). Moreover, trails returned to normal function almost immediately after the event (Table 1, Fig. 3). Case study A exemplified scenario 1. It was located on a ridge, in a forest. Trail slope was moderate (10°). The tread was even with natural stone pavement. The studied section had side-hill trail alignments (at 50° and more), that allowed natural tread drainage and minimised trail erosion. However, case study A had a low slope alignment (25°), that potentially could be difficult to drain. In case study A, proper tread drainage features such as water bars existed downslope, which helped to intercept and drain surface runoff from the tread. The trail was able to accommodate 177 users per day. As the trail was not damaged during the extreme rainfall event, the trail

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could function without disruption and the modelled level of recreational service in this case was constant through time. The mean soil loss observed in transverse profiles for the pre-event period of normal trail functioning was 22.9 mm. The value increased slightly to 25.7 mm during the extreme rainfall. After the event, limited deposition was recorded, but in general, this section of trail remained stable. Trail width was 1.1.-1.6 m and did not change during the seven years of observation.

Table 1. Quantification of the ecosystem service of recreation (modelled capacity of visitors), erosion control (soil loss) and biodiversity as an ecosystem service (loss of vegetation cover) for different scenarios. Notes: (A) Modelled visitor capacity is presented in users/day. Note that in scenario 0 no recreation use was allowed so the modelled visitor capacity is zero. (B) Soil loss is presented as the height difference from ground level immediately following trail construction to the ground level during measurement session. Values in subsequent periods are cumulative values. (C) Loss of vegetation cover is expressed in metres per trail transect. The values in the subsequent periods are cumulative values

Section	Period						
	Pre-event normal functioning	Extreme event	Repair	Natural recovery			Post-event normal functioning
(A) Ecosystem service of recreation: visitor capacity (users/day)							
Scenario 0	0	0	-	-			0
Case study A (scenario 1)	177	0	-	-			177
Case study C (scenario 2)	69	0	35	69			69
Case study B (scenario 2)	90	0	42	56			142
Case study D (scenario 3)	135	0	-	68	68	90	-
Case study E (scenario 3)	73	0	-	73	73	73	-
(B) Ecosystem service of erosion control: change in soil height (trail incision in mm)							
Scenario 0	-0.83	-2.00	-	-			-0.83
case study A (scenario 1)	-22.93	-25.65	-	-			-25.31
case study B (scenario 2)	-10.00	-216.28	-51.25	-54.16			-43.02
case study C (scenario 2)	-40.00	-155.67	-144.22	-150.02			-146.36
case study D (scenario 3)	-5.00	-46.56	-	-49.95	-46.14	-42.57	-
case study E (scenario 3)	-43.38	-52.28	-	-53.23	-71.32	-71.32	-
(C) Ecosystem service of biodiversity maintenance: change in vegetation cover (trail width in m)							
Scenario 0	0	0	-	-			0
case study A (scenario 1)	-1.1	-1.1	-	-			-1.1
case study B (scenario 2)	-0.6	-1.1	-2	-1			-1
case study C (scenario 2)	-1.45	-1.65	-2.45	-1.8			-1.45
case study D (scenario 3)	-0.6	-0.6	-	-0.8	-1	-1	-
case study E (scenario 3)	-2.65	-2.65	-	-2.85	-2.85	-2.85	-

'-' not applicable

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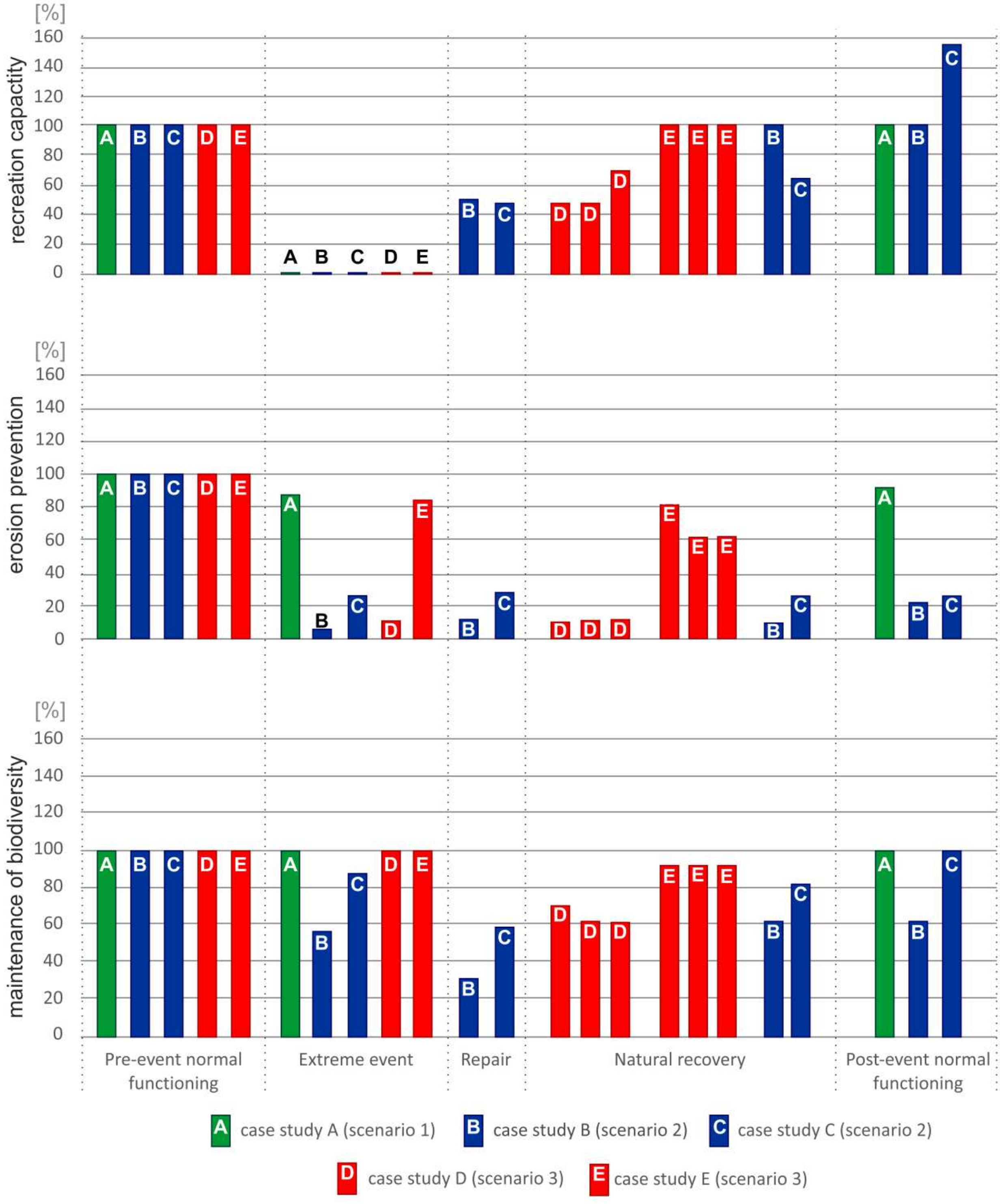

Figure 3. Changes in the supply of ecosystem services for different scenarios of trail functioning after the extreme rainfall event. Baseline value (pre-event) is 100% for each indicator. The values in the following periods are provided in relation to the pre-event value.

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Figure 4. (a) Case study A – an example of a trail which was not damaged during the intense rainfall event which occurred in May 2010. (b) Case study B – an example of trail damage (development of an erosional rill) and the appearance of the trail after repair (scenario 2).

4.3.3. Scenario 2 – trail degradation and repair

Scenario 2 represented trails which were seriously damaged in May 2010, mainly by very intense surface water runoff and soil erosion, but were then subjected to urgent repairs, which included refilling and hardening of trail treads and building of wooden steps or logs. In some cases, trails were closed for recreational use and traffic was re-routed.

Case study B illustrated scenario 2. The analysed section of trail was very steep (22^{o}) and routed parallel to the main slope. Before the extreme rainfall, the trail was narrow, with a natural surface and no incision. The intense rainfall and subsequent surface water runoff eroded a rill, up to 0.85 m deep and up to 1.1 m wide (Fig. 4b), which created difficult and unsafe travel conditions, and forced the park managers to repair this section. In summer 2010 the rill was filled and wooden steps were installed, and visitors could use this section again safely. Shortly after the management action, as the trail was still steep and there was no trailside vegetation, surface water runoff and erosion occurred along the steps. Subsequent growth of vegetation and gathering of litter slowed these processes in the following two years.

The modelled trail capacity for case study B was 69 users per day before the intense rainfall in May 2010 (Table 1, Fig. 3). Immediately after the event and while the trail was under repair, the capacity dropped to 35 users per day. The management action restored the capacity of the trail to the same level as before the rainfall event (69 users per day).

Soil loss in a period of normal trail functioning was low (10 mm) (Table 1). The intense rainfall in May 2010 caused extremely high soil erosion, with mean value of 216.3 mm. As a result of the trail repair action, the rill was filled with rocks and gravel and also steps were installed, thus soil loss in relation to the original slope surface was 51.25 mm. Throughout the time of the trail recovery, soil erosion occurred along the trail sides and mean soil loss increased slightly to 54.2 mm. Subsequent vegetation restoration limited the rate of soil loss to 43 mm in 2014. As a consequence of rainfall damage, the trail widened from 0.6 m to 1.1 m (Table 1). In addition, the management action caused temporary vegetation loss up to 2 m wide. However, in next two years, as a result of system recovery, vegetation cover increased and trail width was restricted to the width of the steps (1.0-1.1 m). The cost of the management action amounted to about 2,000 PLN (~ 550 USD).

Another example of scenario 2 was case study C located below Kudłoń summit (1274 m a.s.l.). The trail was aligned parallel to the prevailing slope and had a steep grade (19^{o}). The tread was unhardened, 1.45 m wide and incised by up to 0.4 m (Fig. 5a). As a result of the intense rainfall in May 2010 and subsequent surface water runoff, trail incision was deepened up to 0.5 m. Trail restoration took place in summer 2010. The trail was re-routed to lower the gradient and avoid 'fall-line' alignment. Additionally, steps made of native rock and wood were installed as a new, durable tread. This management action had significant improvements for both visitor safety and the quality of recreational experience. In addition, it restricted visitor traffic to

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the newly-installed durable tread, minimising damage to the trailside vegetation.

The modelled trail capacity was 56 users per day before the extreme event in May 2010 (Table 1, Fig. 3). In the course of trail rebuilding after the damage caused by the rainfall event, the capacity dropped to 42 users per day. After the restorative management had been completed, the capacity of trail improved to 142 users per day.

Soil loss in the period of normal trail functioning (before May 2010) was 40 mm (Table 1). As a consequence of the intense rainfall, average soil loss increased to 155.7 mm. Although a part of the trail was excluded from recreational use, soil erosion and minor deposition were recorded, mainly due to the steep slope and lack of vegetation. In the following years of observation, erosion and deposition were still documented and in 2014 the average soil loss in relation to the original surface of the slope was 146.4 mm. The width of the trail tread increased from 1.45 m to 1.65 m due to the extreme rainfall event. Subsequent repairs caused additional loss of vegetation cover up to 2.45 m, as the new trail tread was designed and constructed (Table 1). The cost of the management action amounted to about 2,000 PLN (~ 550 USD).

4.3.4. Scenario 3 – trail degradation and natural restoration

Scenario 3 represented trails impacted by surface water runoff and soil erosion during the intense rainfall event in May 2010. However, the trails were not so severely damaged as those in scenario 2, and for this reason no immediate repairs were required. As a result, natural restoration processes occurred.

Case study D illustrated scenario 3. It was located in an extensive glade. Trail tread was natural, routed parallel to the prevailing slope, and trail grade was 13°. Prior to May 2010, the trail was narrow (0.6 m) and not incised (Fig. 5b). As a consequence of the heavy rainfall, erosion resulted in incision of a rill (0.4 m deep and 0.3 m wide) into the trail tread. As this caused walking difficulty, a visitor-created path arose along the damaged trail tread.

Figure 5. (a) Case study C – an example of a trail which has been degraded and repaired. The old course of the trail is marked by yellow survey tapes. After the event, new, less steep course was designed and wooden and stones steps were installed. Note that erosional processes are still active within the old route. (b) Case study D – an example of trail which was degraded and left for natural recovery. Note that before the intense rainfall event, the trail was undamaged and very narrow. In May 2010, an erosional rill developed and as a result of this, visitors created a new path (visible since 2011). During the recovery period, the grass had partly overgrown the rill; however, geomorphological processes were still active.

The modelled trail capacity was 135 users per day prior to the heavy rainfall (Table 1, Fig. 3). After this extreme event, trail capacity lowered, as substantial trail erosion created difficult hiking conditions. Visitors quickly (within one season) developed a new path. However, it was narrower (0.35-0.5 m) than the formal trail tread, and thus the post-event trail capacity was less than before May 2010 – 90 users per day.

Slight incision to the trail was observed during the period of normal functioning (Table 1). However,

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soil erosion (average 46.6 mm) occurred as a result of the heavy rainfall. In the following four years, relief changes were less dynamic, though, in the beginning of recovery period some soil loss was recorded, and the surface of the visitor-created path was compacted. Subsequently, deposition occurred in the incision. Mean soil loss in relation to the original trail surface was 42.6 mm. Trail width was 0.6 m before May 2010, and subsequently increased due to destroyed or trampled vegetation up to 1.1 m (Table 1).

Figure 6. Case study E – an example of trail which had already been degraded before the intense rainfall event. Trail tread was uneven and wide. The extreme rainfall event caused an increase in soil erosion and the rill was deepened.

Case study E was another example of scenario 3. The analysed section was steep (16^{o}) and routed along the edge of the glade. Trail tread was natural and directed obliquely to the prevailing slope. Prior to May 2010, it was 2.65 m wide and a small erosional rill (up to 0.1 m deep) was developed along the trail (Fig. 6). As a consequence of water runoff during the intense rainfall event, the rill was deepened.

The modelled trail capacity in the period of normal functioning (before May 2010) was low - 73 users per day - due to tread roughness and high trail steepness. After the rainfall event, modelled trail capacity was the same (Table 1, Fig. 3).

Mean soil loss in the period of normal functioning (prior to the extreme event) was 43.4 mm (Table 1). It increased during the intense rainfall event to 52.3 mm. The trail became rougher and more prone to erosion. Hence, no natural restoration was observed. On the contrary, at this site, soil loss increased (up to 71.32 mm), and the trail section widened 0.20 m in the period 2010-2014 (Table 1).

5. Discussion

5.1. National Parks and their role in the supply of ecosystem services

National Parks are protected areas, designed to conserve bio- and geodiversity as well as to provide recreational opportunities to society (Dudley, 2008). Recreation opportunities can be maximised by the implementation of appropriate management actions including development and maintenance of National Park infrastructure (Niedziałkowski et al., 2014; Rannow et al., 2014; Watson et al., 2014). Many studies have also identified proper trail management as enhancing recreational use of National Parks (Dixon et al., 2004; Hawes et al., 2013; Leung and Marion, 2000; Marion and Leung, 2001, 2004; Monz et al., 2010; Pickering et al., 2010). Most of these previous works were related to the overall problem of trail condition and degradation related to their utilization (e.g. Ballantyne and Pickering, 2015; Barros et al., 2013; Cakir, 2005; Leung and Marion, 1996; Marion et al., 2006; Marion and Olive, 2006; Monz et al., 2013; Olive and Marion, 2009; Pickering et al., 2010; Tomczyk and Ewertowski, 2011, 2013b; Törn et al., 2009; Wimpey and Marion, 2010). However, in this study, we have used an ES perspective to highlight some of the additional benefits that can result from effective trail management. The most important ES provided by National Parks are recreation and biodiversity conservation. In case of mountain regions, the provision of additional regulating services, such as soil erosion prevention and flood mitigation can also be very significant. Therefore, managers of National Parks in these areas face a difficult task in order to minimise potential trade-offs between these ES.

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Recreational trails are effective management tools to this effect, as they facilitate access to protected areas, hence increasing recreation opportunities, and at the same time limit the penetration of visitors to parts of PNAs that are more sensitive ecologically, hence protecting biodiversity and other regulating services.

5.1.1. Effects of intense rainfall on ecosystem services provision

The extreme rainfall which occurred in May 2010 within GNP decreased recreational opportunities and erosion prevention. However, the limitation of recreational opportunities was restricted not only to the period of severe weather conditions, but persisted beyond this time, depending on trail characteristics. For degraded sections, rehabilitation had to be conducted to restore the original recreation capacity of the trail (scenario 2).

Decrease in the ES of erosion prevention was related to the fact that the water retention capacity of the soil (or rather the landscape in general) was exceeded (Bissolli et al., 2011), causing surface water runoff and an increase in soil erosion. In some cases, depending on the condition of trails (design, construction and maintenance) and after-the-event management activities, soil erosion remained a problem four years after the extreme event, regardless whether the trail was subsequently repaired artificially (scenario 2) or left for natural restoration (scenario 3) (Fig. 3). As a consequence of soil loss, biodiversity loss was recorded in some places, especially when trail users created a new path (case study D) or temporal vegetation loss resulted from repair works (case study B and C).

Therefore, poorly-designed trails, which are more susceptible to damage during heavy rainfall events, will suffer reduced recreation capacity, a decline in erosion prevention and a loss of biodiversity, with some or all of these declines in ES provision potentially long-lasting. Subsequent investments to repair damaged trails are required to recover ES (e.g. case study B and C), but for biodiversity and regulating services, it can take some time for the positive effects of these repairs to be realised (Fig. 3).

As well as causing impacts on the GNP itself, the intense rainfall also had adverse impacts in the surrounding areas. It has been noted that tourism and climate are linked and weather conditions can influence the amount of visitors in specific area (cf. Amelung et al., 2007; Hamilton et al., 2005; Martín, 2005; Smith, 1993). Extreme rainfall can therefore have an impact on the local economy. A decrease in the number of visitors might cause a decrease in income for local people, as many of them rent rooms to visitors and sell other goods and services. An additional negative effect was a limitation in flood mitigation. The increase in soil erosion and water runoff resulting from the intense rainfall event caused an increase in flooding in the surrounding area, where several bridges and roads were destroyed. Similar negative effects were also reported from other regions of Polish Carpathians during the intense rainfall in May 2010 (Kijowska-Strugała, 2012).

5.1.2. Tool for avoiding trade-offs

As has been mentioned above, the intense rainfall event caused a decrease in recreational opportunities as well as a decrease in the regulation of soil erosion. To restore these ES, trail rehabilitation was needed. The monetary cost of trail rehabilitation at the scale of the whole Park undertaken between 2010 and 2015 was 1,935,930 PLN (approximately 530,000 USD), a figure far in excess of normal trail maintenance (10,000 – 20,000 PLN per year).

Leaving trails for natural restoration is one potential alternative to trail rehabilitation. However, our observation indicated that even on trail sections which were excluded from recreational use, soil erosion still took place (cf. case study D and E). Soil erosion on abandoned forest roads in GNP was also indicated by Wałdykowski (2006) and Wałdykowski and Krzemień (2013). Hence, changes in trail course and natural restoration of old trail routes in many cases are not sufficient to bring about effective and timely recovery of damaged ES. Moreover, restoration to pre-event levels of provision is related

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to additional costs in terms of monetary values (scenario 2) or environmental consequences (scenario 3). This was not the case for more properly-constructed trails, which were able to survive the high-intensity rainfall event without significant damage.

There are several examples of using different types of models which can be useful for planning of recreational trail routes to avoid or minimize negative impacts (e.g. Ferrarini et al., 2008; Snyder et al., 2008; Tomczyk and Ewertowski, 2013a; Xiang, 1996). These models can be also extended to incorporate knowledge of local stakeholders, for example by use of the results of map-based interviews (Austin et al., 2009; Irvine et al., 2009) or information about attractiveness of landscape to visitors (Blasi et al., 2005; Daniel, 2001; Goossen and Langers, 2000; Krause, 2001). Apart from proper planning, trails need to be constructed optimally to provide recreation in a sustainable way, and there are several guidelines for trail construction in different environmental settings (Crimmins, 2006; Hesselbarth et al., 2007; Marion and Leung, 2004; Marion and Wimpey, 2007; USDA, 2006; Zeller et al., 2006). Our work has showed that the proper design and construction of recreational trails can bring co-benefits in terms of ecosystem services, by avoiding damage to biodiversity and regulating ecosystem services such as erosion prevention. Trail construction can therefore be seen as one of the solutions enabling Park managers to avoid potential negative trade-offs related with the recreational use of designed protected areas.

6. Conclusions

In this study, we have analysed the impacts of an extreme natural event on ES provision. We used Gorce National Park (Poland) to illustrate how the intense rainfall which occurred in May 2010 affected the supply of recreational opportunities from protected natural areas, but also had implications for biodiversity and the ecosystem service of erosion prevention. The most important findings were:

1) The intense rainfall event which occurred in May 2010 impacted heavily the supply of ES by limiting potential recreation opportunities and reducing erosion prevention.
2) The negative impacts were not only restricted to the period of the extreme event, but persisted for up to several years, depending on the pre-event trail conditions and post-event management activities.
3) To restore the pre-event capacity of supply of ES, economic investments were required in the form of active repairs to trails.
4) When recreational trails were left to natural restoration, loss of biodiversity was observed, and recovery rates of ES (recreation opportunities and soil erosion prevention) were reduced in comparison to pre-event state.
5) Proper trail design and construction provides a good solution to avoid some of the negative impacts of extreme events on recreation, as well as offering co-benefits in terms of protecting biodiversity and the supply of regulating services such as erosion prevention.

Our findings have direct implications for managers of protected natural areas in which recreation is an important activity, as they have demonstrated that negative effects of extreme natural events on recreation and other ecosystem services can be avoided or minimised by a proper understanding of trail functioning and its co-benefits.

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